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Smart Energy Evolution Road-map Based On the Correlation Between Energy and Information

George You Zhou^{a*}, C.C. Chan^b, Ding Zhang^a, Shujun Mu^a, Yi Zong^c, Shi You^c

^aNational Institute of Clean-and-Low-Carbon Energy, NICE, Future Science & Technology City, Changping District, Beijing 102211, China

^bDepartment of E&E Engineering, University of Hong Kong, Hong Kong 999077, Hong Kong

^cDepartment of Electrical Engineering, Technical University of Denmark, Kongens Lyngby 2800, Denmark

Abstract

Smart energy system has been widely accepted as the key pathway for the application of clean energy towards low carbon society. It is normally considered as a portfolio of technologies integrated with energy generation, storage and application driven by information based control mechanism. From the historical review of technology development, the correlation between Energy and Information is first analyzed via the concept of entropy. A novel theoretical perspective of energy digitization is then proposed from analogous linkage between energy storage and data storage. A smart energy road-map is further derived to show how energy eco-system can be self-organized with energy intelligence that is quantifiable with clear physical meaning. In the end, Fractal structure based evolution is concluded to be the key stage for smart energy system, as it drives the fundamental principal between energy and information from proposed theoretical framework.

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Keywords: Smart Energy; Storage Entropy; Energy Intelligence; Fractal Structure

1. Introduction

Smart energy system has been studied thoroughly from various perspectives^[1, 2], with focus on particular energy generation, storage or application technologies as well as architecture design, planning and operation optimization.

* Corresponding author. Tel.: +86-010-57339889; fax: +86-010-57339889.

E-mail address: zhouyou@nicenergy.com

Interactive design methodology between plant and control is common practice for energy industry and academic communities. Multiple energy assets are intended to be combined into one system via integration of energy flow, information flow and material flow with complex network behaviors. The major challenges for system to be smart are: Firstly, system behaviors are highly related to the way how energy assets are being organized and collaborated, which can result into many hidden dependences for potential failures and performance degrading; Secondly, fundamental principle and mechanism of interactions between different energy assets are not fully understood, which causes major barriers for effective planning and optimization design. Thirdly, theoretical framework to bridge energy and information flow has not been fully formed to prove there exists one quantified parameter to indicate intelligent level of energy system so that smart behavior of energy system can be measurable. All these challenges have prevented a standard integration rule for smart energy system to be an economic viable solution.

This paper intends to look at integrated energy system from different perspective based on the analogy between energy and information flow so that a quantifiable intelligence index called “energy intelligence” can be derived to guide the system to follow an evolutionary road map for life-cycle sustainability. By reviewing the development path of both technologies, we found that information intelligence is evolved from information flow discretization based on major theoretical breakthrough from Shannon information theory. Similarly, the correlated nature of energy flow^[3,4] is analyzed via the introduced “storage entropy” concept, which can also take advantage of energy flow discretization to increase energy intelligence. Based on this correlation, a new theoretical framework and related smart energy road-map is derived. The key challenges towards implementation are discussed with proposed fractal structure from energy storage, which already exists at different spatial and temporal level in clean energy system.

2. Observation--- Correlation between Energy and Information

Information has been the key for self-organized evolution of human society for thousands of years. It has not been well understood and being measurable until the invention of information theory introduced by Shannon^[5] in 1948. This theory is quickly accepted by industry via the technology breakthrough on digital implementation from transistor, register, processor to computer, internet and IoT. The era of information technology (IT) has changed the world and created values more than the sum of previous 5000 years. Similarly, Energy has been the key for the growth of society. Most people consider it has been digitized as it can be controlled by digital technology from computerized device to IoT driven network. In this paper, we tend to define the energy digitization from different perspective, based on the analogy with information technology:

- 1) The nature of information digitization is to discretize information flow such as sound, pic & video etc. via Analog to Digital (ADC) conversion, then store them into register, which can be further formed as memory, such as cache, USB, hard-drive or cloud etc. The digitized information is processed in digital format, transmitted via internet and converted back to needed format such as sound, pic & video etc. via Digital to Analog (DAC) conversion, which is shown in Fig. 1a.
- 2) In analogy, the introduction of intermittent renewables has changed the nature of energy flow from continuous to discrete mode. A power electronics based smart grid will act as the backbone of energy internet and nearly all energy format can be converted into electricity and connected to the grid via power converters, which could be considered as the energy ADC and DAC as shown in Fig. 1b. Energy storage thus can be naturally considered

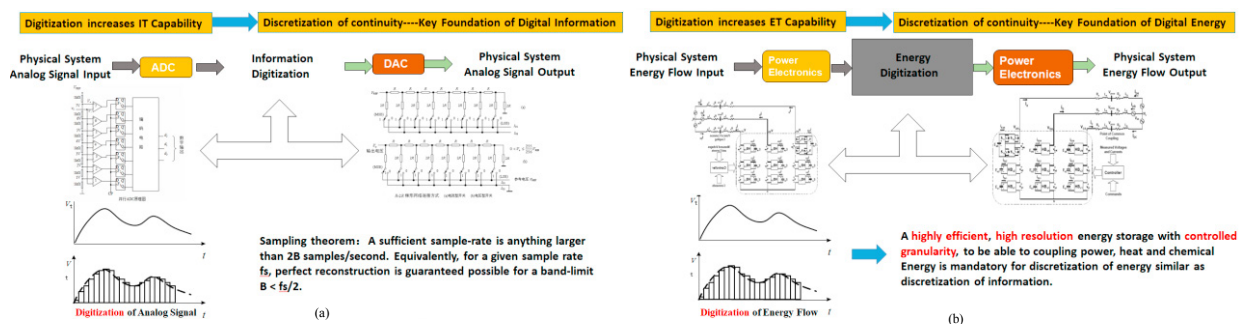


Fig. 1 (a) The digitization increases IT capability; (b) As an analogy, the digitization increases ET capability.

as energy memory, which is highly cost-sensitive as data memory at beginning but will eventually be cost-effective driven by advancement in fundamental research along with large volume adoption in application. Both energy and data storage show similar cost/value model per storage need at different temporal and spatial scales.

Existing energy formats such as power/heat/Chemical energy etc. look measurable in continuous mode, just as information looks measurable for sound, pic and video. But Information is not accurately quantifiable until the definition of BIT from Shannon entropy, as shown below:

$$S = -k \sum_{i=1}^n P_i \log P_i \quad (1)$$

The physical meaning of Shannon entropy is the measurement of information uncertainty, which could be understood as measurement of particle state uncertainty for energy system when W microstates possibility of particles is considered, as shown below:

$$S = -k \sum_{i=1}^W \frac{1}{W} \log \frac{1}{W} \quad (2)$$

$$\rightarrow S = \sum k \ln W \quad (3)$$

Eq. (3) is the definition of famous Boltzmann entropy. The above derivation shows there is a fundamental correlation between energy & information, which possibly leads to an analogous smart energy system framework with similar development pathway as information technology.

3. Reasoning ---A new path way for smart energy

Strictly Speaking, theoretical frame work in ET industry, similar as Shannon theory, has not been successfully developed towards energy digitization. Most distributed energy systems are not smart enough to be economically viable as we simply do not know if we can or how to quantify an index level for energy intelligence. For instance, we can neither evaluate the behaviors between different micro-grids nor between present and past status for the same micro-grid. This has prevented energy industry to create standard integration principle and evaluation rule at

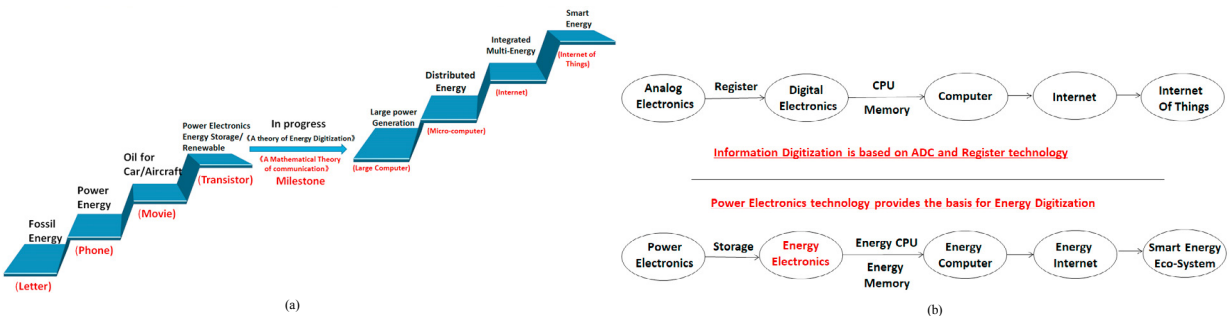


Fig. 2 The similar pathway between ET & IT (a) The progress of energy digitization; (b) The energy electronics analogy to digital electronics.

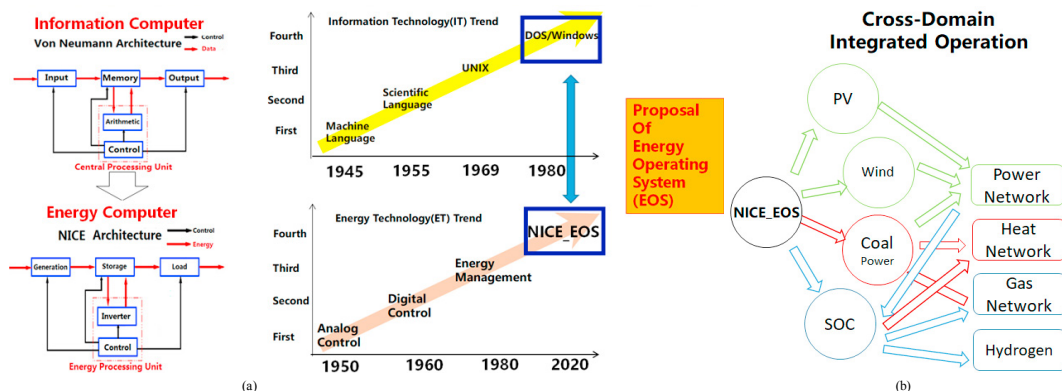


Fig. 3 (a) The structure of Energy computer; (b) The application of Energy Operating System(EOS)

system level.

Based on the similar pathway between ET & IT as shown in Fig. 2a & 2b, we try to define power electronics & energy storage as the implementation form for “energy memory” device to support the discretization of energy flow, which could be further developed into an “energy computer” structure for distributed energy system as shown in Fig. 3a. Similarly, as how information technology has developed Operating System (OS) based software layer to manage hardware in a generic fashion, an Energy Operating System (EOS) framework could also be developed for the successful integration of multi-energy based system operation as shown in Fig. 3a & 3b.

4. Concept---Storage Entropy

In an integrated multi-energy system, interactive energy flow and information flow are the key contributors to drive the system to be smart and sustainable. There is no fundamental principle built so far to explain how the intelligence of the system grows and whether it can be quantifiable based on these internal interactions. As entropy is the key correlation concept between energy and information as described in previous sections, we try to use entropy theory to build the bridge and help to quantify energy intelligence level for an energy system. Firstly, we will briefly review the concept development history of entropy as shown in Fig. 4. The most unique concept is the introduction of negentropy by Schrodinger, which directs the pathway towards building the order of a system.

In the dissipative structure theory developed by Prigogine, the entropy structure of isolated system is compared with open system as shown in Fig. 5a. Internal entropy $d_i S$ is driven by internal irreversible process and can only increase. External entropy $d_e S$ is driven by external process and can be positive / negative or zero, as shown below

$$dS = d_i S + d_e S \quad (4)$$

When we consider an eco-system is formed by two systems as shown in Fig. 5a, the total entropy of the eco-system will be derived based on

$$\left. \begin{aligned} dS_1 &= d_{i1} S + d_{e1} S \\ dS_2 &= d_{i2} S + d_{e2} S \end{aligned} \right\} \rightarrow dS = dS_1 + dS_2 - dS_s \quad (5)$$

A new term dS_s is introduced to show the entropy contribution caused by the interactive behavior between two systems, this entropy is defined as storage entropy and it could be positive, negative or zero. The physical meaning

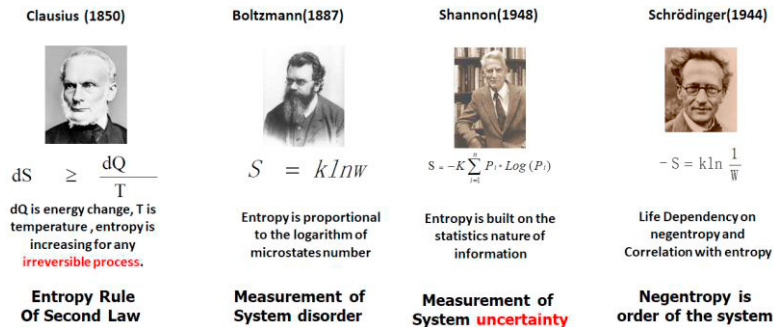


Fig. 4 The history of entropy concept development

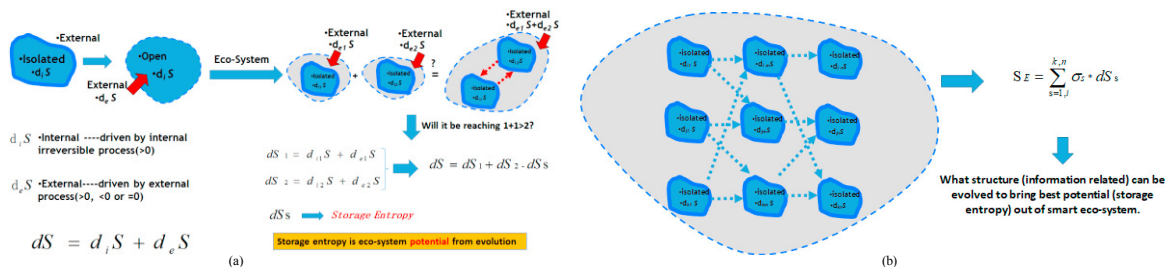


Fig. 5 (a) The entropy structure of isolated system is compared with open system and eco-system is formed by two systems; (b) The Storage entropy of a complex network system.

of storage entropy is given below:

- 1) When storage entropy is positive, it means the interaction between two systems has enhanced the capability of both to apply work, therefore, the total entropy of the system is decreasing, which means the system tends to be more self-organized and smarter with higher intelligence level. This is normally considered as the impact of “1+1>2” for a team work, as both actively exchange useful information to bring each other’s potentials out to create more work.
- 2) When storage entropy is negative, it means the interaction between two systems has decreased the capability of both to apply work, therefore, the total entropy of the system is increasing, which means the system tends to be less self-organized and less smart with lower intelligence level. This is normally considered as the impact of “1+1<2” for a team work.
- 3) When storage entropy is zero, it means no interaction may happen between two systems.

Overall, Storage Entropy represents energy that is not-usable at present time but is usable in the future if there is information flow with other systems. A more generic equation could be derived based on Fig. 5b. as shown below: If we use H_s to define information entropy for information flow between two systems, energy intelligence of system thus can be defined as T_E and introduced as (E_s represents Exergy energy converted from storage entropy by H_s)

$$T_E = \sum_{s=1,1}^{k,n} \sigma_s \frac{f(dS_s)}{H_s} = \sum_{s=1,1}^{k,n} \frac{dE_s}{H_s} \quad (6)$$

The physical meaning of system intelligence actually represents system capability to turn storage entropy dS_s into exergy energy dE_s based on per unit information of H_s . For a thermal-dynamic system, this equation will become

$$T_E = \sum \frac{dE_s}{H_s} = \frac{dQ}{dS} = T \quad (7)$$

This means the energy intelligence of a thermal-dynamic system can be represented by its temperature T , which shows its capability of applying work.

5. Theory---Fractal Energy System

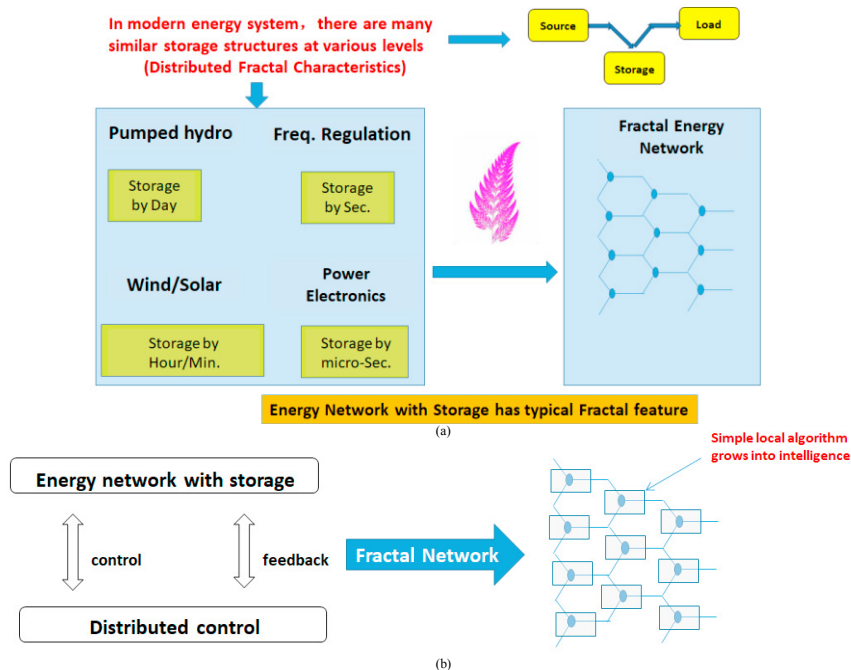


Fig. 6 (a) Energy storage shows fractal structure at different temporal and spatial scale in multi-energy integrated system; (b) Sophisticated system energy intelligence is expected to grow out of fractal energy network based on simple local algorithm.

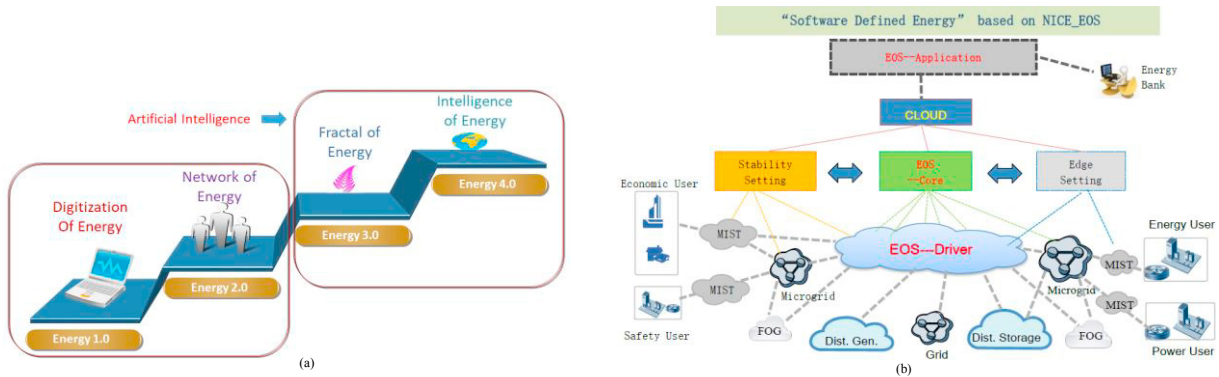


Fig. 7 (a) The evolutionary road-map for smart energy; (b) A Software-Defined-Energy Framework built upon NICE_EOS.

The definition of energy intelligence in Eq. (6) shows that if using minimized information flow can maximize storage entropy conversion into exergy energy, system will have highest energy intelligence and highest capability to apply work. For a complex network based energy system, entropy of information flow is highly dependent on the structure. It has been proven to some extent^[6, 7] that, self-organized intelligent network tends to grow into fractal structure with self-similar and scale-free features. As shown in Fig. 6a, energy storage has been observed to show fractal structure at different temporal and spatial scale in multi-energy integrated system. Sophisticated system energy intelligence is expected to grow out of local simple algorithm if fractal energy network system can be successfully designed based on the fundamental framework proposed in this paper, as shown in Fig. 6b.

6. Result ----Smart Energy Road-map

With the introduction of fractal energy system, we here present an evolutionary road-map for smart energy as shown in Fig. 7a. Energy 1.0 is the stage to focus on the computerization of energy equipment. Energy 2.0 is the stage to develop the integrated multi-energy network, which is the status of existing technology level. Energy 3.0 is the key stage to drive the system to gain self-organization capability that is highly dependent on the correlation between energy flow & information flow based on energy storage driven fractal structure. Energy 4.0 is the future stage with advanced machine learning intelligence for smart energy system. Overall, a Software-Defined-Energy Framework built upon NICE_EOS can be implemented to support the proposed road-map, as shown in Fig. 7b.

7. Conclusion

This paper has proposed a new perspective of energy digitization based on the correlation between energy and information. A novel energy entropy concept is introduced to describe the interactive behaviors within smart energy eco-system. A quantifiable definition of energy intelligence is derived under clear physical meaning, which leads to a smart energy framework with self-organization capability to grow while being sustainable. A smart energy road-map is finally presented to show that fractal based structure design from energy storage is the key stage for energy system evolution.

Acknowledgements

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